CLAIMS

What is claimed is:

1.   1.   A method of timing recovery of symbols in a received signal, comprising the steps
2   of:

3   (a) generating a sequence of samples from the received signal with a sample period and
4   sample phase related to a symbol rate of the symbols;

5   (b) generating a phase error for a current sample from the sequence based on a gradient of
6   a blind cost criterion of Bussgang-class cost functions;

7   (c) adjusting at least one of the sample period and sample phase based on the phase error
8   such that a magnitude of the phase error is driven to a predetermined point; and

9   (d) repeating steps (a), (b), and (c) for subsequent samples.

1   2.   The invention as recited in claim 1, wherein step (b) comprises the steps of:

2   (b1) calculating a blind cost error term based on the sample;

3   (b2) forming an approximation of a derivative of the received signal with respect to the
4   sampling phase; and

5   (b3) combining the blind cost error term and the approximation to form the phase error.

1   3.   The invention as recited in claim 1, wherein step (b) comprises the steps of:

2   (b1) calculating a blind cost error term based on the sample; and

3   (b2) forming an approximation of a derivative of the received signal with respect to the
4   sampling phase.

1   4.   The invention as recited in claim 3, further comprising the steps of (e) generating
2   a quality measure for the received signal from the sequence; and wherein step (b1) further
3   comprises the step of generating at least one other cost function error term based on a
4   corresponding cost function criterion.

1   5.   The invention as recited in claim 4, further comprising the steps of:

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2   b3) selecting an error value, based on the quality measure, as either the blind cost error

3   term or one cost function error term; and

4   b4) combining the error value with the approximation to form the phase error.

1   6.   The invention as recited in claim 4, further comprising the steps of:

2   b3) selecting an error value, based on the quality level, as a weighted combination of the

3   blind cost error term and the at least one other cost error term as the error value; and

4   b4) combining the error value with the approximation to form the phase error.

1   7.   The invention as recited in claim 4, wherein, for step (b) the at least one cost

2   function error term includes a least mean squares error term.

1   8.   The invention as recited in claim 4, wherein, for step (b) the quality measure is

2   based on at least one of a signal-to-noise ratio (SNR) of the received signal, SNR of a trellis

3   decoder employed to detect each symbol, a number of symbols received, errors within a number

4   of symbols received and detected, and vestigial sideband signal (VSB) framelock.

1   9.   The invention as recited in claim 3, wherein, for step (b), either i) the blind cost

2   criterion is a Constant Modulus (CM) cost criterion and the gradient is the CM algorithm or ii)

3   the blind cost criterion is a Single-axis Constant Modulus (SA-CM) criterion and the gradient is a

4   SA-CM algorithm.

1   10.   The invention as recited in claim 9, wherein, for step (b) the CM cost criterion J_{CM}

2   is expressed as:

3
$$J_{CM} = E[(\rho^2 - |y_n(\tau)|^2)^2],$$

4   wherein ρ^2 is a dispersion constant, $y_n(\tau)$ is a discrete value representing the current

5   sample generated at the sampling period, and τ represents the sampling phase; and

6   wherein the gradient is $dJ_{CM}/d\tau$ and is expressed as:

7
$$dJ_{CM}/d\tau = (dJ_{CM}/dy_n(\tau))dy_n(\tau)/d\tau,$$

8   wherein the derivative of the signal with respect to the sampling phase is $dy_n(\tau)/d\tau$ and a

9   derivative of J_{CM} with respect to $y_n(\tau)$ is the blind cost error term determined as:

10 $$y_n(\tau)(\rho^2 - |y_n(\tau)|^2).$$

1   11.   The invention as recited in claim 1, wherein, for step (b), the phase error is

2 generated in accordance with a phase error calculation derived for a cost function error criterion

3 having a corresponding cost function error term, the phase error calculation substituting the blind

4 cost error term for the cost function error term.

1   12.   The invention as recited in claim 11, for step (b) comprises the steps of:

2   (b1) calculating a blind cost error term for a current sample $y_n(\tau)$ and a blind cost error

3 term for a previous sample $y_{n-1}(\tau)$, based on a gradient of a constant modulus (CM) cost criterion;

4 and

5   (b2) combining the current and previous blind cost error terms with the current and

6 previous samples generated at the sampling period to generate the timing phase error as:

7 $$y_n(\tau)y_{n-1}(\tau)\left((\rho^2 - |y_n(\tau)|^2) - (\rho^2 - |y_{n-1}(\tau)|^2)\right)$$

8 where ρ^2 is a dispersion constant and τ represents the sampling phase.

1   13.   The invention as recited in claim 1, wherein, for step (a) the received signal is

2 demodulated from either a *m*-ary quadrature amplitude modulated (QAM) signal, a *m*-ary offset

3 QAM signal, an *m*-ary phase-shift keyed modulated (*m*-ary PSK) signal, a vestigial sideband

4 modulated (VSB) signal, a pulse amplitude modulated (PAM) signal, a signal modulated in

5 accordance with a CCITT 802.11 standard, or a signal modulated in accordance with a V.27

6 standard.

1   14.   The invention as recited in claim 1, wherein, for step (b), the Bussgang-class cost

2 function is selected from either a Godard cost function, Benverniste-Goursat-Ruget cost function,

3 or a Sato cost function.

1   15.   The invention as recited in claim 1, wherein the method is embodied in a

2 processor of an integrated circuit.

1   16.   The invention as recited in claim 15, wherein the integrated circuit is embodied in

2 a demodulator of a high definition television signal.

1   17.   The invention as recited in claim 1, wherein, for step (a), the received signal is a

2   vestigial sideband (VSB) modulated signal, and, for step (b) the blind cost criterion is a Single-

3   axis Constant Modulus (SA-CM) criterion and the gradient is a SA-CM algorithm.

1   18.   The invention as recited in claim 1, wherein, for step (a), the received signal is a

2   digital television signal having data encoding and modulation in accordance with an ATSC

3   standard.

1   19.   Apparatus for timing recovery of a symbol rate for symbols in a received signal,

2   comprising:

3   a timing reference providing a reference signal;

4   a sample generator configured to generate a sequence of samples from the received signal

5   with a sample period and sample phase based on the reference signal and related to the symbol

6   rate;

7   a blind cost error term generator configured to generate a blind cost error term for a

8   current sample of the sequence in accordance with a gradient of a blind cost criterion of

9   Bussgang-class cost functions; and

10   a timing phase detector configured to generate a phase error for the current sample from

11   the sequence and based on the blind cost error term;

12   wherein the timing reference modifies the reference signal based on the phase error to

13   adjust at least one of the sample period and sample phase such that a magnitude of the phase

14   error is driven to zero.

1   20.   The invention as recited in claim 19, wherein the timing phase detector forms an

2   approximation of a derivative of the received signal with respect to the sampling phase; and

3   combines the blind cost error term and the approximation to form the phase error.

1   21.   The invention as recited in claim 20, wherein the timing phase detector includes a

2   filter having a delay chain receiving the sequence and a combiner, and the combiner forms the

3   derivative of the signal with respect to the sampling phase by generating the difference between a

4   previous sample from a corresponding delay of the delay chain and the current sample.

1   22.   The invention as recited in claim 20, wherein the blind cost criterion is the

2   Constant Modulus (CM) cost criterion and the gradient is the CM algorithm, and wherein the

3   blind cost error term is generated by:

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5   ii) forming the gradient of the CM cost criterion as $dJ_{CM}/d\tau$ expressed as:

6                    $dJ_{CM}/d\tau = (dJ_{CM}/dy_n(\tau))dy_n(\tau)/d\tau,$

7   wherein the CM cost criterion J_{CM} is defined as:

8                    $J_{CM} = E[(\rho^2 - |y_n(\tau)|^2)^2]$

9   in which ρ^2 is a dispersion constant, $y_n(\tau)$ is a discrete value representing the current sample

10   generated at the sampling period, and τ represents the sampling phase; and

11   wherein the derivative of the received signal with respect to the sampling phase is

12   $dy_n(\tau)/d\tau$ and a derivative of J_{CM} with respect to $y_n(\tau)$ is the blind cost error term given by

13                    $y_n(\tau)(\rho^2 - |y_n(\tau)|^2).$

1   23.   The invention as recited in claim 19, wherein the phase detector generates the

2   phase error in accordance with a phase error calculation derived for a cost function error criterion

3   having a corresponding cost function error term, the phase error calculation substituting the blind

4   cost error term for the cost function error term.

1   24.   The invention as recited in claim 23, wherein the blind-cost error term is based on

2   a gradient of a constant modulus (CM) cost criterion for the current sample defined as

3                    $dJ_{CM}/d\tau = (dJ_{CM}/dy_n(\tau))dy_n(\tau)/d\tau,$

4   wherein $J_{CM} = E[(\rho^2 - |y_n(\tau)|^2)^2]$ is the CM cost criterion, ρ^2 is a dispersion constant, $y_n(\tau)$ is a

5   discrete value representing the current sample generated at the sampling period, τ represents the

6   sampling phase, and $dy_n(\tau)/d\tau$ is a derivative of the received signal with respect to the sampling

7   phase is $dy_n(\tau)/d\tau$, and a derivative of J_{CM} with respect to $y_n(\tau)$ is defined as the blind cost error

8   term $e_{CMA}[n]$ given by

9                    $e_{CMA}[n] = y_n(\tau)(\rho^2 - |y_n(\tau)|^2);$ and

10   wherein the timing phase detector combines a current blind cost error term $e_{CMA}[n]$ and a

11   previous blind cost error term $e_{CMA}[n-1]$ with the current sample $y_n(\tau)$ and previous sample $y_{n-1}(\tau)$

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12   to generate the timing phase error as:

13    $$y_n(\tau)y_{n-1}(\tau)\,((\rho^2 - |y_n(\tau)|^2) - (\rho^2 - |y_{n-1}(\tau)|^2))$$

1   25.   The invention as recited in claim 19, wherein the sample generator comprises an

2   analog-to-digital (A/D converter) configured to generate a sequence of discrete values from the

3   received signal.

1   26.   The invention as recited in claim 25, wherein the timing reference is an oscillator

2   coupled to the A/D converter, and the A/D converter generates the sequence of discrete values so

3   as to convert the received signal to the sequence of samples with the sampling phase and the

4   sampling period.

1   27.   The invention as recited in claim 25, wherein the sample generator further

2   comprises an interpolator coupled to the A/D converter and coupled to the timing reference

3   generator, wherein the interpolator is configured to adjust the sequence of discrete values from

4   the A/D converter to form the sequence of samples with the sampling period and the sampling

5   phase.

1   28.   The invention as recited in claim 25, wherein the received signal is demodulated

2   from either a *m*-ary quadrature amplitude modulated (QAM) signal, a *m*-ary offset QAM signal,

3   an *m*-ary phase-shift keyed modulated (*m*-ary PSK) signal, a vestigial sideband modulated (VSB)

4   signal, a pulse amplitude modulated (PAM) signal, a signal modulated in accordance with a

5   CCITT 802.11 standard, or a signal modulated in accordance with a V.27 standard.

1   29.   The invention as recited in claim 19, further comprising 1) a signal quality

2   processor generating a signal quality measure (SQM) signal, and 2) at least one cost function

3   error generator, each cost function error generator configured to generate a cost function error

4   term with a corresponding cost function criterion.

1   30.   The invention as recited in claim 19, further comprising a multiplexer selecting

2   either the blind cost error term or at least one cost function error term based on the SQM signal;

3   and

4   wherein the timing phase detector, based on the SQM signal, either i) provides the phase

5   error generated with the blind cost error term or ii) provides the phase error based on the selected

6   cost function error term from the multiplexer.

1   31.   The invention as recited in claim 29, further comprising a weighting mechanism

2   circuit, the weighting mechanism circuit forming, based on the SQM signal, a weighted

3   combination of i) the blind cost error term with ii) the at least one cost function error term, and

4   wherein the timing phase detector, based on the SQM signal, generates the phase error with the

5   weighted combination.

1   32.   The invention as recited in claim 29, wherein the SQM signal is based on at least

2   one of a signal-to-noise ratio (SNR) of the received signal, SNR of a trellis decoder employed to

3   detect each symbol, a number of symbols received, errors within a number of symbols received

4   and detected, and ATSC frame synchronization acquisition.

1   33.   The invention as recited in claim 19, wherein the blind cost error generator is

2   included in an adaptive equalizer, the blind cost error generator forming the blind cost error term

3   to update equalizer coefficients.

1   34.   The invention as recited in claim 19, wherein the Bussgang-class cost function is

2   selected from either a Godard cost function, Benverniste-Goursat-Ruget cost function, or a Sato

3   cost function.

1   35.   The invention as recited in claim 19, wherein the apparatus is embodied in an

2   integrated circuit.

1   36.   The invention as recited in claim 35, wherein the apparatus is embodied in a

2   demodulator of a high definition television signal.

1   37.   The invention as recited in claim 19, wherein the received signal is a vestigial

2   sideband (VSB) modulated signal, and the blind cost criterion is a Single-axis Constant Modulus

3   (SA-CM) criterion and the gradient is a SA-CM algorithm.

1   38.   The invention as recited in claim 19, wherein the received signal is a digital

2   television signal having data encoding and modulation in accordance with an ATSC standard.

1   39.   A computer-readable medium having stored thereon a plurality of instructions, the

2   plurality of instructions including instructions which, when executed by a processor, cause the

3   processor to implement a method for timing recovery of symbols in a received signal, the method

4   comprising the steps of:

5   (a) generating a sequence of samples from the received signal with a sample period and

6   sample phase related to a symbol rate of the symbols;

7   (b) generating a phase error for a current sample from the sequence based on a gradient of

8   a blind cost criterion of Bussgang-class cost functions;

9   (c) adjusting at least one of the sample period and sample phase based on the phase error

10   such that a magnitude of the phase error is driven to zero; and

11   (d) repeating steps (a), (b), and (c) for subsequent samples.

1   40.   The invention as recited in claim 39, wherein step (b) comprises the steps of:

2   (b1) calculating a blind cost error term based on the sample;

3   (b2) forming an approximation of a derivative of the received signal with respect to the

4   sampling phase; and

5   (b3) combining the blind cost error term and the approximation to form the phase error.